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A Wearable FES Compression Garment †

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Abstract: Functional electrical stimulation is commonly used as a rehabilitation therapy to support the movement of individuals who have suffered traumatic spinal cord injury. Recently, there has been a focused interest on the development of textile electrodes, as they pose many benefits over traditional electrodes. This study presents design considerations and the feasibility of a wearable FES garment sleeve using flexible and extensible screen-printed electrodes.

Keywords: functional electrical stimulation; textile electrodes; e-textiles; spinal cord injury rehabilitation; wearable technology

1. Introduction

Functional electrical stimulation (FES) has long been utilised as a rehabilitation therapy to stimulate muscle activity and support the movement of individuals who have suffered traumatic spinal cord injury [1,2]. In the last decade, there has been a focused interest to develop textile electrodes for FES applications as they pose a number of potential advantages over the use of traditional hydrogel electrodes [3]. One practical advantage of textile electrodes is their extended lifetime in comparison to hydrogel electrodes, as textile electrodes are designed to be laundered and reused multiple times.

In general, there are two main routes to the manufacturing of textile electrodes; knitting, weaving, or embroidering with conductive yarns, and screen-printing with conductive inks onto fabric. Such flexibility of manufacture allows opportunity for the specific tailoring of textile electrodes to the end-use. For the purpose of this study, the textile electrodes are required to exhibit enhanced flexibility and extensibility to provide adequate compression within a garment, whilst maintaining stimulation efficiency.

However, despite the potential of wearable FES garments, the stimulation comfort of textile electrodes remains of concern [3]. For example, researchers [3,4] found that textile electrodes produced by knitting technologies required continued moistening to exhibit comparable stimulation performance to traditional electrodes. There has also been an increased focus on the development of dry-contact textile electrodes. Hydrogel electrodes cannot be used long term, as moisture evaporation reduces their performance. The feasibility of dry-contact flexible screen-printed polymer electrodes has been demonstrated by Yang et al. [1] in the form of small electrode arrays.

The novelty of this research is the development of a proof-of-concept wearable FES compression garment sleeve with dry-contact stimulation electrodes that are both flexible and extensible. The FES sleeve has been developed for quadricep stimulation by applying screen-printed electrodes to polyamide-elastane knitted fabric. Stimulation performance of size-matched, screen-printed, and traditional hydrogel electrodes was assessed by measuring knee extension torque at prescribed stimulus intervals.

2. Materials and Methods

2.1. Fabrication of the Wearable Sleeve

A wearable FES garment was produced by integrating screen-printed electrodes, provided by Conductive Transfers UK Limited, into a compressive quadricep sleeve. The parameters of the wearable are listed in Table 1. Screen printed electrodes were applied at 165 °C with a medium pressure for 12 s to polyamide-elastane blend knitted fabric. Two electrodes were used during the study and each electrode was applied to an individual sleeve; therefore, two sleeves were used. The compression administered to the participant by the FES sleeve was measured in millimetres of Mercury (mmHg) using Microlab PicoPress equipment.

Table 1. Parameters of the FES (Functional Electrical Stimulation) sleeve.

Electrode Type	Fabric Base	Fabric Construction	Width (mm)	Length (mm)	Fastening
Screen-printed	polyamide-elastane	knitted	120	550	Hook and loop (Velcro)

2.2. Measurement of Muscle Torque during Stimulation

Stimulation was prescribed to one male able-bodied participant at 30 Hz square wave form pulses at 10 mA intervals generated for 2 s, with a step current gradually increasing at 10 mA intervals. Experimental parameters can be viewed in Table 2. Cybex dynamometer equipment was used to obtain quadricep torque measurements in nanometers (Nm) during each stimulation event. A comparison of the measurement of quadricep muscle torque trace was made for both traditional hydrogel and screen-printed electrodes.

Table 2. Parameters of the electrodes use for quadricep muscle torque stimulation testing.

Type	Contact Type	Quantity	Shape	Diameter (cm)
Standard Hydrogel	wet	2	circular	7
Screen-printed	dry	2	circular	7

3. Results

3.1. The Design and Usability of the Wearable Sleeve

A compressive FES sleeve was developed; images are presented in Figure 1. Ease of usability of the FES garment was of great importance to this study as the intended end-user may have experienced spinal cord injury resulting in loss of movement in the lower half of the body. Therefore, design variables such as electrode placement, fastening system, and easy donning and doffing were optimised for these considerations.

(**a**) (**b**)

Figure 1. Images of the FES sleeve: (**a**) Front side with electrode and Velcro fastening; (**b**) Back side.

Preliminary work was conducted by the research group that investigated the effect of sleeve compression on the resistance of screen-printed electrodes and found that compression levels above 3–5 mmHg to have little beneficial effect on electrode impedance. For this study, it was found that a knitted polyamide–elastane blend fabric administered an average compression reading of 11 mmHg, which therefore ensured adequate compression during stimulation to maintain electrode–skin contact. The fabric blend and construction also allowed flexibility and extension required for muscle activation during stimulation and facilitated easy donning and doffing.

The positioning of the wearable electrodes was based on the standard location used by practitioners when stimulating the quadriceps with traditional hydrogel electrodes [5]. In practice, it is common to adjust the placement of gel electrodes at first to find the adequate positioning. This removal and reapplication of gel electrodes can damage the delicate hydrogel layer, resulting in ineffective adhesion at the skin–electrode interface. On the other hand, once the wearable FES sleeve had been applied to the leg, the dry-contact screen-printed electrodes allowed for adjustment of the sleeve without having to remove and reapply the sleeve.

During prototyping stages, a range of garment fastening types were considered with the main requirement being easy to don and doff for the user. Both zip and hook and loop (Velcro) fastening were evaluated and it was found that, due to the elastane content of the fabric and the compressive nature of the garment, feeding the teeth into the zip slider whilst the sleeve was being held around the quadriceps proved more problematic compared to the Velcro fastening. Instead, the Velcro sleeve was favoured because, as one end of the sleeve containing the 'hook' side of the Velcro strip was held in place, the other side containing the 'loop' strip was easily pulled to overlap and secure the fastening.

3.2. Results of Screen-Printed and Hydrogel Electrode Stimulation

The experiment started with an initial current administered at 10 mA; however, a torque reading was not recorded for either the hydrogel or screen-printed electrodes. The results for torque trace during stimulation for both screen-printed and hydrogel electrodes are shown in Figure 2. For the hydrogel electrodes, the torque trace was activated at 30 mA (9 Nm) and increased with increasing current intervals up to 44 Nm at 60 mA. At 60 mA, the observed movement of the participant was significant but not described as uncomfortable by the participant.

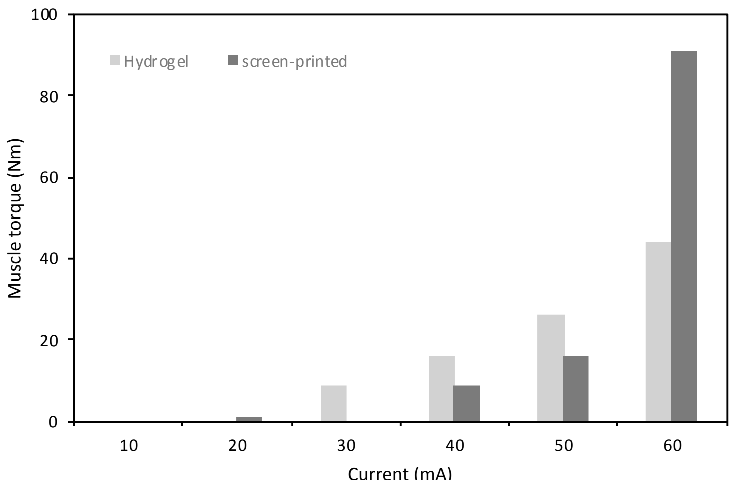

Figure 2. Torque trace as a function of current.

In the case of the FES garment, a negligible torque trace of 1 Nm was recorded at 20 mA for screen-printed electrodes; there was then no activation until 40 mA, unlike the hydrogel electrodes, where significant activity was recorded at 30 mA. The initial torque trace of 9 Nm was comparable to the first torque trace given by the hydrogel electrodes at 30 mA. Similarly, at 50 mA, the screen-printed electrodes registered a torque trace of 16 Nm, comparable to the hydrogel reading at 40 mA. Although the torque measurements for the screen-printed electrodes at 40 and 50 mA were around 10 mA lower than the hydrogel electrodes, they followed the same increase pattern. The screen-printed electrodes were used as dry-contact electrodes, and so it is possible that higher current was required to activate the targeted muscle group.

However, an unexpected effect was observed at the 60 mA current interval. The recorded torque activity considerably increased for the screen-printed electrodes, surpassing the reading for the hydrogel electrodes at the same current reading. At 60 mA, the torque activity recorded was 91 Nm, which is 75 Nm higher than the 50 mA reading and 47 Nm higher than the hydrogel electrode at 60 mA. It was noted that the participant described stimulation as unpleasant at this stage. It is possible that increased perspiration, due to the nature of the sleeve covering a larger surface area of the thigh, compared to hydrogel electrodes, caused a significant decrease in impedance. Another possibility is a disturbance in the electrode–skin contact area of the sleeve, leading into an uneven contact area and therefore a localized high current flow. However, the research project is ongoing and this remains to be investigated.

4. Conclusions

This study has demonstrated the design and feasibility of a wearable FES garment proof of concept using screen-printed electrodes. The results have provided an opportunity to improve the use of textile electrodes for FES applications. From a usability perspective, the fabrication of the FES garment sleeve provided the required measured compression level for optimised electrode–skin contact and facilitated easy donning and doffing. It was found that the initial torque reading for the FES sleeve was activated at a 10 mA higher current interval compared to hydrogel electrodes but followed a similar pattern of increase in torque at current intervals until 60 mA. At 60 mA current stimulation, the screen-printed electrodes exhibited a significant increase in torque measurement, this is possibly due to a combination of change in impedance as an effect of perspiration and a high localized current flow as a result of an uneven electrode–skin contact area. Future work will continue to develop and refine the stimulation performance of wearable FES garment electrodes, as well as conducting a pilot trial with a clinical population.

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